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Soil Moisture Retrieval Using the Danish L- & C-Band Polarimetric SAR

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ABSTRACT – Danish polarimetric SAR data have been applied to estimate soil moisture (SM). The preliminary results evaluated with the L- and C-band SAR data acquired at the Danish test site Foulum during a number of missions in 1994 and 1995 are presented. *In situ* data have been collected during the SAR missions and the variations of SM at field scale are discussed. The Integral Equation Method (IEM), the Dubois empirical model and the Oh polarized-ratio model have been used as algorithms to inverse SM from polarimetric SAR data under near bare field conditions. Comparisons between the inversions and the *in situ* measured data showed that the Dubois empirical model gave the best results for inversion of SM. The standard deviations between the inversed and the measured data at C-band are $s_{m_v} = 6.1\%$ for SM and $s_\sigma = 0.37cm$ for soil surface *rms* height, respectively. C-band data are better than L-band data for estimation of surface roughness.

INTRODUCTION

The principle of radar measuring soil moisture (SM) is that the backscattering coefficient varies strongly with the soil dielectric constant, and the latter depends on the SM content. Unfortunately, soil surface roughness and vegetation cover also have strong contributions to the backscattering coefficient. Thus, it is difficult to retrieve SM from single polarization radar data. A polarimetric SAR measures the full polarimetric signatures of targets and the ambiguity implied in backscattering coefficients from the contributions of SM, roughness and vegetation might be removed by evaluating the polarimetric signatures of backscattering coefficients, which makes SM retrieval from polarimetric SAR data possible.

The tool to infer SM from SAR data is backscattering models. It has been realized that the classical surface backscattering models have some limitations when applied to natural surfaces [1]. Therefore, the Integral Equation Model (IEM), valid in a large range of roughness conditions is currently widely used as a theory for soil scatter [1]. In addition, Dubois and Oh have developed two different empirical models [2, 3]. The empirical models are much simplified compared to the IEM. In this paper, the Danish L- and C-band polarimetric SAR data acquisitions and the *in situ* data collections are described. SM variations at field scale are illustrated. The Dubois model, the Oh model and the IEM have been applied for SM retrieval.

THE POLARIMETRIC SAR DATA

The Danish polarimetric SAR (EMISAR) was initially a C-band VV-polarized SAR first flown in 1989 and later in 1993 a fully polarimetric system. An L-band system with fully polarimetric capability was completed and tested early 1995. The EMISAR is developed by the Danish Center for Remote Sensing (DCRS) located at the Department of Electromagnetic Systems (EMI) of the Technical University of Denmark (DTU) [4].

The test site Foulum used for agriculture study is located in the northern part of Jutland, Denmark. Four different fields were selected as the test fields. There were four C-band acquisitions during 1994 and a number of L- and C-band acquisitions during 1995 over the test site, respectively. Polarimetric one-look images with spatial resolution of $2m$ by $2m$ are used in the study. One C-band scene acquired on April 28, 1994, a number of L- and C-band scenes acquired in 1995, for instance, on March 22 (L), March 24 (C), April 27 (C), May 1 (L), June 8 (L), and August 25 (L), are processed for SM retrieval. The incidence angles for all the four test fields are between $42° - 45°$.

FIELD EXPERIMENT DESCRIPTION

Corresponding to the EMISAR acquisitions from the beginning of March to the end of August both 1994 and 1995, extensive *in situ* data collections have taken place at the 4 test fields under conditions ranging from bare soil to fully vegetated. The vegetation types were winter wheat, spring barley, sugar beet and grass. All relevant parameters for interpretation of EMISAR images were measured

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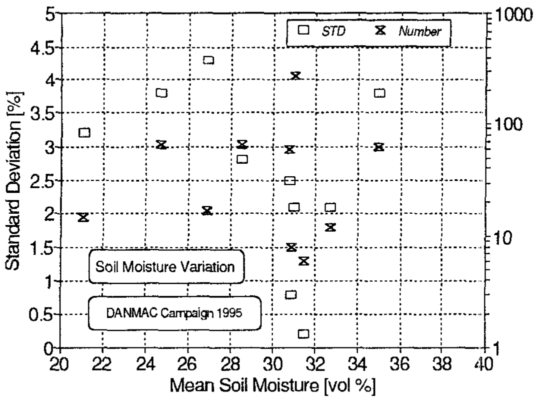

Figure 1: *In situ* SM vs. Standard Deviation (STD) and number of samples.

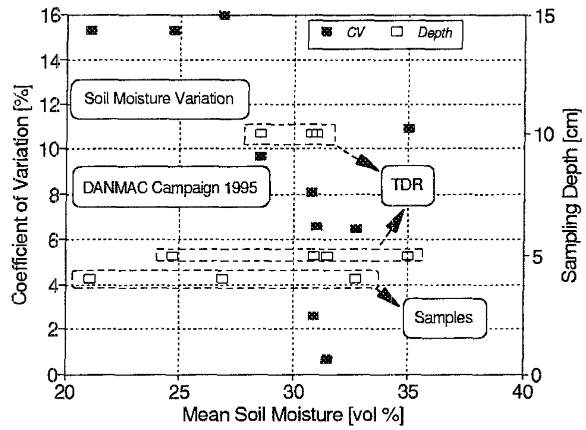

Figure 2: *In situ* SM vs. Coefficient of Variations (CV) and sampling depth.

in this period, including surface roughness, surface SM, Leaf Area Index (LAI) and other biophysical parameters such as vegetation water content, biomass and plant density and height.

Surface roughness was measured by a 2 meter long ruler and, later in the growing season, by a laser instrument, developed at the Research Center Foulum (RCF). SM was measured along transects for each 25 meter and in two grids, a 50 meter by 50 meter grid in the winter wheat field and a 150 meter by 150 meter grid in the spring barley field. Water content in the top 0-5cm and 0-10cm was determined by gravimetric sampling using $100cm^3$ sampling rings (4cm in depth) and by Time Domain Reflectometry (TDR) with 5 and 10cm long probes. Leaf Area Index was monitored by the LAI2000 device (Licor). Biomass and water content in vegetation was sampled manually together with estimates of plant density and height. Climatological data were collected during the whole period from March to September. Furthermore, continuous TDR measurements of water content were made in a 60cm deep soil profile in the spring barley field.

SM VARIATIONS AT FIELD SCALE

In situ SM was measured at each sampling point with 6 samples for the TDR and 3 samples for the sampling rings, respectively. Mean values of the measured water contents are plotted against standard deviations and the number of samples in Fig. 1. Volumetric water content is calculated as the product of soil bulk density and gravimetric water content. Bulk density varies normally between 0.8 and $1.4g/cm^3$, sometimes caused by sampling in and outside tractor wheel tracks. However, the standard deviation of the volumetric water content never exceeds 4.5%, which is in agreement with findings by Bell *et al.* [6].

The Coefficient of Variation (CV) in Fig. 2 is 16% or lower. Bell *et al.* [6] state that for mean SM higher than 20 vol.% CV is generally less than 15%, a value which is desirable for SM-brightness temperature correlations.

SM AND *rms* HEIGHT RETRIEVAL

The theoretical IEM, the Oh's polarized ratio model and the Dubois's co-polarized backscattering coefficient model have been applied to the fields under near bare soil conditions determined by Dubois's criteria $\sigma^\circ_{hv}/\sigma^\circ_{vv} < -11dB$ for both L- and C-band [2]. The roughness conditions of the fields fall into the validity regions of these models. Dobson's dielectric constant model has been used to convert between dielectric constant and SM [7].

Inversion with the IEM

The measured roughness data show that the hybrid Gauss-Exp function which is the product of Gaussian and exponential functions is a suitable form for autocorrelation function (ACF) [5], and there is approximately a linear relation between the correlation length l and the rms height σ for a natural soil surface. In the inversion with the IEM, the hybrid Gauss-Exp function is used for the ACF and l is replaced by the linear correspondence with σ. Results of the inversion from numerical fit of the IEM to the SAR data show that the IEM underestimates SM, and a rms error of 10.0% is obtained. This underestimation is equivalent to an overestimation of the backscattering coefficient. A recent study indicates that one reason may be that the surface roughness measured *in situ* does not resemble the roughness relevant for the radar backscattering. The radar signal is probably backscattered by a smoother subsurface layer.

Inversion with the Oh Model

Oh developed a polarized ratio model in 1992 and modified it in 1994 [3]. Unfortunately, only few of the EMISAR data could be inversed with both versions of the model, and the agreement was poor between the inversed and the measured SM. One reason might be that the model uses both co- and cross-polarized ratios. Cross-polarized ratio has a larger uncertainty compared to co-polarized backscatter because of the poorer signal-to-noise ratio.

Inversion with the Dubois Model

Figs. 3 shows the inversed SM and the *rms* height using the Dubois model. The *rms* errors between the inversed and the measured m_v are 7.6% (L-band, $N = 7$) and 6.1% (C-band, $N = 11$), and the *rms* errors for σ are 0.65*cm* (L-band, $N = 12$) and 0.37*cm* (C-band, $N = 12$), respectively. The Dubois model gave the best results of the three. There is no preference of L- or C-band for SM inversion, but for *rms* height inversion C-band gave the best results, and the *rms* error is very close to that of Dubois, 0.35*cm* [2]. The *rms* height results also show that the Dubois model seems to overestimate σ for $\sigma < 0.5cm$ and to underestimate σ for $\sigma > 0.5cm$.

The validity conditions of a model are important. Most of the theories and most of the SAR observations illustrate that the backscattering coefficient $\sigma^o_{hh}/\sigma^o_{vv} \leq 1$ for bare soil. Dubois *et al.* indicated that restricting the validity of the model to $k\sigma < 2.5$ and $\theta \geq 30^\circ$ will ensure that $\sigma^o_{hh}/\sigma^o_{vv} \leq 1$, where k is wavenumber, θ is incidence angle. Using this equation, we can study the validity conditions from the expressions of the Dubois model, which is $k\sigma \leq cos^5\theta sin^{\frac{20}{3}-1}\theta \cdot 10^{\frac{1}{3}(4+0.18\epsilon_r tan\theta)}$, where ϵ_r is the real part of the relative dielectric constant. It is obvious that the roughness conditions which the Dubois model can be applied to is related not only to the incidence angle, but also to the soil dielectric constant. For example, at $\theta = 35^\circ$ it is valid when $k\sigma \leq 2.4$ for wet soil ($\epsilon_r \geq 20.0$), but it is only valid when $k\sigma \leq 0.5$ for dry soil ($\epsilon_r \geq 4.0$). This reveals some differences of the validity of the Dubois model by keeping $\sigma^o_{hh}/\sigma^o_{vv} \leq 1$ as the criteria.

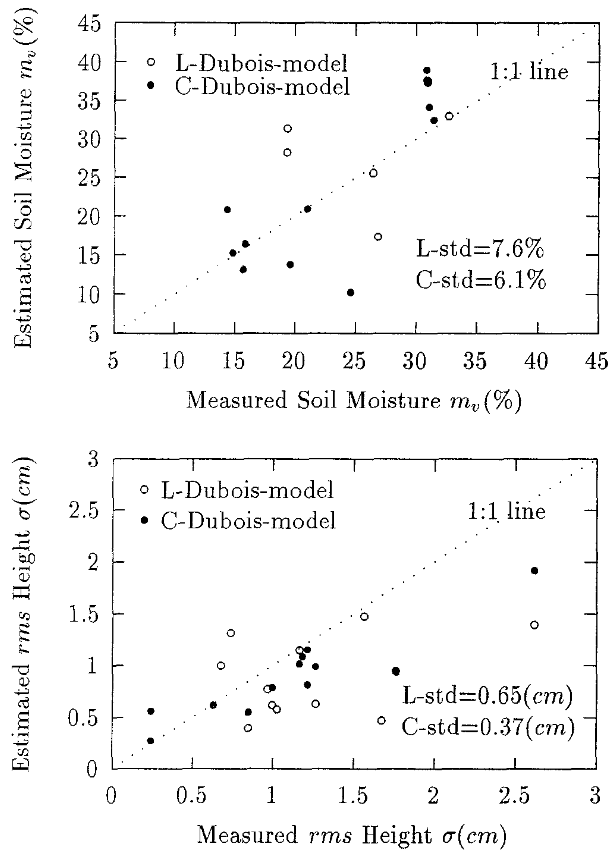

Figure 3: Inversion results using the Dubois model.

CONCLUDING REMARKS

Retrieval of SM with the polarimetric EMISAR data has been presented. The detailed grid measurements of the *in situ* SM data show that the standard deviation of SM at field scale is below 4.5%, which illustrates probably the best accuracy of the SAR measured SM. One can not expect that the accuracy of the SAR measured SM is better than the accuracy of the *in situ* measurement. The Dubois model for inversion of SM showed better results than both the Oh model and the IEM model. The L- and C-band data showed equivalent results for SM retrieval, whereas the C-band data was preferred for the *rms* height retrieval using the Dubois model. The validity condition of the Dubois model has been discussed under the restriction of $\sigma^o_{hh}/\sigma^o_{vv} \leq 1$.

On-going work is focused on two aspects. To improve *in situ* data quality by using a laser instrument to measure the roughness and by increasing the number of samples for SM measurement. To improve the inversion accuracy by modifying the existing models.

ACKNOWLEDGMENTS

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